

Direct Imaging of Domain Wall Interactions in $\text{Ni}_{80}\text{Fe}_{20}$

Planar Nanowires

T.J. Hayward, M.T. Bryan, P.W. Fry, P.M. Fundi, M.R.J. Gibbs and D.A. Allwood

Department of Engineering Materials, University of Sheffield, Sheffield, UK

P. Fischer and M.-Y. Im

LBNL/CXRO, Berkeley, California, USA

We have investigated magnetostatic interactions between domain walls in $\text{Ni}_{80}\text{Fe}_{20}$ planar nanowires using magnetic X-ray microscopy and micromagnetic simulations. In addition to significant monopole-like attraction and repulsion effects we observe that there is coupling of the magnetization configurations of the walls. This is explained in terms of an interaction energy that depends not only on the distance between the walls, but also upon their internal magnetization structure.

The properties of magnetic domain walls confined within planar ferromagnetic nanowires [1] are currently a subject of great research interest. In addition to representing a well-defined nanomagnetic system that is ideal for fundamental studies such domain walls have particle-like properties that allow them to be propagated controllably around nanowire circuits in a manner analogous to the movement of electrical charge in standard microelectronics. This has led to designs for memory [2] and logic devices [3] that use domain walls to separate binary data, represented by uniformly magnetized domains.

Despite a large body of work investigating the structure [1,4,5] propagation [6-9] and pinning [10-12] of domain walls in nanowires, few studies have examined interactions between them [13]. The magnetization of a nanowire lies predominantly along its length to minimize magnetostatic energy. Consequently, domain walls are boundaries between either converging ('head-to-head'; H2H) or diverging ('tail-to-tail'; T2T) magnetization (Fig. 1(a)), and carry an intrinsic magnetic monopole moment.

From this discussion it is expected that domain walls in neighboring nanowires exhibit a Coulomb-like interaction such that walls with monopole moments of opposite signs attract each other, while walls with monopole moments of the same sign repel each other. However, this picture is complicated by walls having non-uniform magnetization structures, for example the "vortex" (Fig. 1(b)) and "transverse" (Fig. 1(c)) configurations, which may modify the interaction when nanowires are in close proximity. Additional complexity is added by the winding number of the wall, which describes the direction of magnetization rotation in

vortex or transverse walls. Understanding how these factors affect inter-wall interactions is not only interesting from the perspective of fundamental physics, but is also likely to be important in device-level implementations where a high density of nanowires is desirable.

Here, we have used magnetic transmission x-ray microscopy (M-TXM) and micromagnetic simulations to study magnetostatic interactions between pairs of domain walls in planar $\text{Ni}_{80}\text{Fe}_{20}$ nanowires. We present evidence of clear attraction/repulsion effects between walls with opposite/like monopole moments and substantial coupling between the magnetization configurations of the two walls, indicating that their interaction energy depends on both their structure and winding number.

Pairs of 440 nm wide magnetic nanowires were fabricated onto Si_3N_4 membranes using electron-beam lithography and lift-off processing. Deposition of a 33nm thick $\text{Ni}_{80}\text{Fe}_{20}$ film was performed by thermal evaporation at a base pressure of $\sim 3 \times 10^{-7}$ mbar. The nanowires were semi-circular in shape, such that saturation in a radial direction followed by relaxation created a bi-domain state consisting of two circumferential domains separated by a H2H or T2T domain wall. Two different pair geometries were fabricated: in the “mirror” geometry, the two wires curve in opposite directions (Fig. 1(d)) and hence domain walls with opposite monopole moments are created following saturation. In the “concentric” geometry, the wires curve in the same direction (Fig. 1(e)), and domain walls with like monopole moments are formed. In each pair of wires the right-hand wire contained a small notch at the right side of its apex in order to create a well-defined domain wall pinning site. Wires with a variety of edge-to-edge separations were fabricated: 50 nm, 100 nm and 200 nm for the mirror geometry, and 150 nm, 200 nm and 500 nm for the concentric geometry.

M-TXM was performed at beamline 6.1.2 at the Advanced Light Source synchrotron [14]. Measurements were made at the Fe L_3 (706 eV) absorption edge. In-plane magnetic contrast was achieved by differential imaging with left and right circularly polarized X-rays, with the sample tilted at 30° to normal incidence. Magnetic fields could be applied both parallel and perpendicular to the direction of magnetic contrast. Further details of the system can be found elsewhere [15].

Micromagnetic simulations were performed using the OOMMF software package [16]. The simulations were performed on a 2D mesh composed of 5 nm x 5 nm cells. Standard parameters were used to represent the material constants of $\text{Ni}_{80}\text{Fe}_{20}$.

To investigate interactions between domain walls each pair of wires was repeatedly saturated using fields of ± 1 kOe, relaxed and imaged. The positions and structures of the two domain walls formed in the wires were analyzed following each reversal.

Initial imaging of isolated domain walls showed that the wires' geometry favored a vortex wall structure, as would be expected from the wires' large dimensions [1,4]. Micromagnetic simulations supported this, showing that a transverse wall had energy 16 % higher than a vortex wall in a wire with the dimensions of the imaged structures.

All of the wall pairs observed in wires with the mirror geometry [e.g. Figs. 2(a)-(c)] were aligned with low displacements from each other, such that the wall centers were separated by a lateral distance no greater than half the apparent vortex wall width. This is consistent with the walls possessing opposite monopole moments and experiencing an attractive interaction. Domain walls in the concentric wire geometry were expected to possess like monopole moments and repel each other. This was observed in the experimental images [e.g. Figs. 2(d)-(f)], which showed the vast majority of wall pairs (56 of the 62 wall pairs observed) separated by at least half the vortex wall width, indicating the presence of a strong repulsive interaction. More closely spaced pairs of walls were only observed in the wire pairs with larger spacing, where the weaker domain wall interactions would make defects more significant in determining wall positions.

In addition to the simple attraction/repulsion effects described above, strong evidence of correlation between the structure and winding number of neighboring domain walls was also observed. In the mirror wires with 50 nm spacing, the walls in each pair had parallel transverse magnetizations structures [Fig. 2(a)]. This configuration was well reproduced in micromagnetic simulations [Fig. 2(a)]. These simulations showed the configuration to be meta-stable, with energy 3.6% higher than the ground state of two vortex walls with identical circulations. We believe that the meta-stable transverse wall was observed preferentially because it was formed as a precursor to the vortex wall as the wires relax from saturation. The magnetic flux closure between the monopole moments of the domain walls is aligned in the same direction as the transverse magnetization of the transverse walls and hence creates an energy barrier against the twisting required to form a vortex wall.

With an increased spacing of 100 nm, the mirror wires exhibited both pairs of transverse walls and pairs of vortex walls with parallel circulations [Fig. 2(b)]. The interaction between the walls was clearly weaker, and was no longer strong enough to stabilize the transverse wall configurations in all relaxations. The images also showed that the vortex wall pairs were

significantly distorted such that the regions aligned to the flux-closing monopole field were enlarged, while those that opposed it were reduced in size [see for example the micromagnetic simulation result in Fig. 2(b)]. It is significant that no pairs of vortex walls with anti-parallel circulations were observed. This suggests that the energies of pairs of identical and non-identical vortex walls were not degenerate, and hence that the walls' interaction energy depended on their winding numbers.

In the mirror wires with 200 nm spacing vortex wall pairs with both parallel and anti-parallel circulations were observed [Fig. 2(c)]. This indicates a reduced correlation between the domain wall winding numbers in the two wires compared to the pairs with narrower spacing.

For the concentric wires with the lowest spacing (100 nm) strong correlation of the domain wall structures were observed, with all pairs exhibiting vortex domain walls with opposite circulations [Fig. 2(d)]. However, upon increasing the separations to 150 nm wall pairs with both identical and opposite circulations were observed, again appearing to indicate a reduction in the coupling between the structures of the domain walls [Fig. 2(e)]. Finally, in the wires with separations of 500 nm the majority of wall pairs exhibited opposite circulations [Fig. 2(e)].

To gain a more detailed understanding of how the interaction between the domain walls depends on their structure and separation, we performed micromagnetic simulations in which domain wall pairs with a variety of relative displacements were inserted into parallel nanowires. An example configuration from this study is shown in Fig. 3(a). The interaction energy as a function of the position of the upper wall was calculated while the lower wall remained stationary.

Figure 3(b) shows the calculated interaction energy for the concentric wires with 100 nm separation. Data is shown for a pair of H2H clockwise vortex walls (c,c) and a pair of H2H walls with an anti-clockwise vortex in the upper wire and a clockwise vortex in the lower wire (a,c). Clearly, there is an increase in the interaction energy as the walls are brought together, as would be expected from the walls' monopole repulsion. However, there are also subtle differences in the shapes of the two curves such that for a given wall displacement, one configuration is energetically favorable. We believe that this effect is the origin of the correlation between domain wall structures observed experimentally.

The shapes of the curves in Fig. 3(b) can be understood by considering the magnetic pole density distributions within the domain walls, which proportional to $\nabla \cdot \mathbf{M}$ (see Fig. 1(b) and

(c) for $\nabla \cdot \mathbf{M}$ calculated from micromagnetic simulations for vortex and transverse walls). The pole distributions are equivalent to magnetic “charge” distributions and will undergo a Coulomb-like interaction with each other. Switching the winding number or monopole character of the domain walls causes the shape of the distribution to be reflected about a line along the centre of the nanowire. In the case of the (c,c) vortex walls the charge distributions are identical, and hence a positive displacement of the upper wall is not geometrically equivalent to a negative displacement. This causes the shape of the curve to be asymmetric about zero displacement. For the (a,c) pair the pole density distributions mirror each other and hence movement of the upper wall in either direction is equivalent, creating a symmetric energy landscape.

Figure 3(c) shows a similar plot for wires with 50 nm spacing containing one H2H wall and one T2T wall. The energy minimum in each data set shows the attractive monopole interaction for this geometry. The lower energy combination of vortex wall types is again dependent on the wall position, although this time the curve for the (a,c) configuration is asymmetric. Also shown is the interaction energy for a pair of transverse walls (t,t), which produce a much stronger interaction than the vortex walls. This is most likely due to their transverse magnetization creating a dipolar field component which will couple the walls strongly when they are close together. However, this does not make the (t,t) configuration the ground state at this separation, as demonstrated by the dotted line in Fig. 3(c) which shows the interaction energy of the (t,t) state offset by the energy cost of having transverse rather than vortex walls in the wires.

Figure 3(d) shows how the interaction energy landscapes for the mirror wires evolve as the separation between the wires is increased. At larger separations the differences between the (c,c) and (a,c) curves are reduced, which reflects the reduced significance of the magnetic pole spatial distribution within the walls. This also explains the reduced experimental correlation between wall structures at larger separations, since the small energy differences between the domain wall states will become less significant relative to the effects of wire defects and thermal excitations.

Figure 3(e) plots the domain wall interaction energy of the (c,c), (a,c) and (t,t) wall pair states as a function of mirror wire separation, for zero displacement of the upper wall. For comparison, a simple monopole model which assumes that the total pole density of the domain wall is concentrated at its center is also shown. At large separations all four curves are in good agreement, showing that the distribution of magnetic poles in the wall has little effect

on the interaction energy, and hence there will be little or no coupling between the domain walls' structures and winding numbers.

At low (< 200 nm) separations there is significant splitting of the energies of the various states indicating that there will be strong coupling between the structures and winding numbers of the domain walls. Furthermore, at low separations the (t,t) interaction energy is much stronger than that predicted by the monopole model, most likely due to the dipolar effects discussed earlier. In contrast to this, the interaction energy of the vortex walls at low separations is weaker than predicted by the monopole model, perhaps due to the enhanced flux closure that occurs within a vortex wall.

From Fig. 3 it is clear that which wall configuration is favored by the domain wall coupling depends on the walls' relative positions. Figures 4(a) and (b) show the energy difference between the (a,c) and (c,c) configurations ($E_{c,c} - E_{a,c}$) as a function of wall separation, for each of the mirror and concentric wire pairs imaged experimentally. Data for the (t,t) wall pairs is not shown, as these configurations are always meta-stable or unstable for these geometries. Data for other wall configurations can be inferred by considering the symmetry of the walls' pole density distributions, and if necessary mirroring the plots in the x-axis.

Using results of the micromagnetic simulations it was possible to analyze the M-TXM images in more detail and classify each configuration as meta-stable (i.e. transverse walls), stable and "favorable" by structural coupling or stable but "unfavorable" by structural coupling. Bar charts showing the observed prevalence of these states for each geometry are shown in Figures 3(c) and 3(d). Statistical analysis provided further compelling evidence of coupling between the magnetic structures of the walls, with the data from the most closely spaced mirror and concentric wire pairs both confirming the hypothesis that "favorable" and "meta-stable" states were formed preferentially with a significance level < 0.005 %. The data also appears to show the decreasing impact of domain wall structure for increased wire separation. This is particularly evident for the concentric wires, for which a decreasing number of wall pairs were observed in "favorable" configurations as the separation between the wires is increased, until at 500 nm separation 50 % of the observed wall pairs are in "favorable" states and 50 % are in "unfavorable" states, showing that there is no statistically significant interaction between domain wall configurations. A similar trend is also observed for the mirror wires, where "unfavorable" states are only observed at the widest (200 nm) wire separation.

In conclusion, we have used M-TXM and micromagnetic simulations to investigate interactions between domain walls in pairs of planar Ni-Fe nanowires. We have observed attraction/repulsion between domain walls with opposite/like monopole moments. Furthermore, for wire separations < 200 nm we have found that the domain wall interaction energy depends additionally on the magnetization configuration and winding number of the walls. In our experimental results this manifests as the preferential formation of certain domain wall configurations when the nanowires are relaxed from saturation. Our results have particular implications for technologies based the propagation of domain walls through nanowire circuits, which will not only need to compensate for simple monopole type interactions between walls, but also to take account of the specific wall structures present. Further systematic investigations are required to understand how the strength of these interactions depends on the geometry of the nanowires, and the manner in which the interactions are altered in the dynamic regime where domain wall structure can oscillate [17].

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Figure Captions

Figure 1: (a) Schematic diagrams of a head-to-head and a tail-to-tail domain wall. (b) Magnetization structure (\mathbf{M}) and magnetic pole density plot ($\nabla \cdot \mathbf{M}$) produced from a micromagnetic simulation of a vortex wall in a 33 nm thick, 440 nm wide NiFe nanowire. (c) Magnetization structure and magnetic pole density plot for a transverse wall in a 20 nm thick, 440 nm wide nanowire. (d) Schematic diagram and scanning electron microscopy (SEM) image showing the “mirror” wire pair geometry. (e) Schematic diagram and scanning electron microscopy (SEM) image showing the “concentric” wire pair geometry.

Figure 2: (a)-(c) M-TXM images showing domain wall configurations observed in the “mirror” geometry nanowire pairs, in which the domain walls possess opposite monopole moments. Micromagnetic simulation results showing a pair of coupled transverse walls and a pair of vortex walls distorted by the magnetic field closing between the walls are also shown in (a) and (b) respectively. (d)-(e) M-TXM images showing domain wall configurations observed in the “concentric” nanowire pairs, in which the domain walls possess alike monopole moments.

Figure 3: (a) Image showing the geometry simulated to measure the interaction energy between domain wall pairs. The lower wall is assumed to be pinned while the upper wall is displaced to vary the wall separation. (b) Interaction energy as a function of wall displacement for a pair of concentric wires with spacing 150nm. Data is shown for a pair of clockwise H2H walls (c,c) and for a pair with an anticlockwise wall in the upper wire and a clockwise wall in the lower wire (a,c). The data is offset by the interaction between the wires end domains. (c) Equivalent plot for a pair of mirror wires with spacing 50 nm. The upper and lower wires have T2T and H2H character respectively. In addition to the (c,c) and (a,c) wall pairs data is also shown for a pair of transverse walls (t,t). The dashed line shows the (t,t) data offset by the energy cost of having transverse, rather than vortex walls in the nanowires. (c) Interaction energy for mirror wires with separations of 50 nm (circles), 100 nm (squares) and 200 nm (triangles). Data for both (c,c) pairs (open symbols) and (a,c) pairs (filled symbols) is shown. (d) Interaction energy as a function of wire pair separation for zero wall displacement. Data is also shown for a simple monopole model.

Figure 4: (a) $E_{a,c} - E_{c,c}$ as a function of wall displacement for the mirror wire geometry. The dashed line shows the approximate boundary between positions where (a,c) and (c,c) wall pairs are favourable. Spacings: 50 nm (circles), 100 nm (diamonds) and 200 nm (triangles).

(b) Equivalent plot for the concentric wire geometry. Spacings: 150 nm (circles), 200 nm (diamonds) and 500 nm (triangles). (c) and (d) bar charts of the states observed in the experimental images of the nanowire pairs. The filled bars represent stable configurations which are made favorable by the coupling between the domain walls' magnetization structures. The unfilled bars represent stable configurations which are made unfavourable by the same effects. The hashed bars represent metastable transverse wall pairs.







